Phasing out hard coal from energy production in Finland

Master's Thesis

Johanna Luomaranta

Environmental Economics

Faculty of Agriculture and Forestry

University of Helsinki

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

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Tiivistelmä/Referat – Abstract

The parties of the Paris Climate Agreement agreed on stopping the global warming to 2°C compared to the pre-industrial level and to make efforts to keep the temperature rise below 1,5°C. Finland among other countries has set goals for the future to meet the wanted emission reductions. The plan is to increase the use of renewable energy sources to be over 50 % of the final consumption, increase energy self-sufficiency to more than 55 %, give up hard coal in the energy production, cut the domestic use of imported oil to half and raise the share of renewable fuels in traffic to 40 % until the year 2030. The long-term goal is to have a completely carbon neutral society by the year 2050.

Hard coal, peat and natural gas have been the most utilized fuels in combined heat and power (CHP) production among different wood fuels. The share of hard coal in CHP production is significant in some parts of Finland. Approximately 90 % of hard coal consumed in energy production in Finland in the year 2016 was used for CHP production in 8 different localities. Most of these are planning on switching to other energy sources during the years 2025-2030.

There are several possibilities to integrate renewable energy sources to a district heating system. For example heat pumps, waste heat, geothermal energy, solar energy, biogas, biomass and waste energy can all be utilized in a district heating system. Biomass is considered to be the number one alternative to conventional energy sources among CHP and heat production. For example heat pumps and waste heat are also planned on being utilized and in Helsinki natural gas a well.

Hard coal use in energy production in Finland is regulated through the European Union emissions trading system and nationwide taxation. The Finnish Parliament has decided on a law against the use of hard coal and it will come into effect in 2029. Giving up hard coal in energy production affects largely in Helsinki. 30 % of all hard coal used in energy production in Finland was burned in Helsinki and 60 % of district heat in Helsinki was produced with hard coal.

This thesis seeks to find out the optimal tax based on emissions from hard coal that will cause hard coal to phase out from the markets. It is studied with an energy business model. The model is used to maximize the profit of different energy production methods: CHP plant consuming hard coal and wood pellet, heat only boiler (HOB) burning wood pellet and heat pump. The numerical applications are based on the situation of Helen energy company in Helsinki.

According to the numerical applications the yearly profit of Salmisaari B power plant in Helsinki is 33,27 million euros when the emission allowance price is 20 €/tCO^2. This more or less represents the current situation. The yearly emission reduction of giving up hard coal use in the CHP power plant would be approximately one million tCO^2. Investing to HOBs burning wood pellets and producing heat the same amount as Salmisaari B power plant leads to yearly profit of 9,77 million euros. A tax of 21 €/tCO^2 in addition to an emission allowance price of 20 €/tCO^2 would be needed to make the pellet-burning HOBs more profitable than burning hard coal.

Investing to several heat pumps in order to produce heat a similar amount to the Salmisaari B CHP plant would gain yearly profit of 20,95 million euros. For this investment to be profitable compared to hard coal a tax of 11 €/tCO^2 would need to be imposed in addition to an emission allowance price of 20 €/tCO^2.

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1. Introduction

The Paris Climate Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 was made to speed up the fight against climate change. The aim is to keep the global temperature rise below 2°C compared to the pre-industrial level and furthermore strive to keep it below 1,5°C.

The European Union has set its climate and energy policy targets until the year 2030. The most essential of these is the objective to reduce greenhouse gas (GHG) emissions by 40 % compared to the level of the year 1990. The emission reduction target has been divided to be 43 % from the Emission Trading Scheme and 30 % from the Efforts Sharing Sectors compared to the emission level of the year 2005. Countries of the European Union have committed to reduce their GHG emissions by 80-95 % by the year 2050 compared to the level of the year 1990. (Ministry of Economic Affairs and Employment 2017.)

The former Finnish Prime Minister Juha Sipilä and his Parliament set ambitious goals for the energy sector. The aim is to increase the use of renewable energy sources to over 50 % of the final consumption, increase energy self-sufficiency to more than 55 %, give up hard coal in the energy production, cut the domestic use of imported oil to half and raise the share of renewable fuels in traffic to 40 % until the year 2030. The long-term goal is to have a completely carbon neutral society by the year 2050. (Ministry of Economic Affairs and Employment 2017.)

A significant part, 74 %, of the GHG emissions from Finland is formed in the energy sector. Total GHG emissions from Finland in the year 2017 were 55,4 Mt of carbon dioxide equivalent. The GHG emissions among the energy sector were 41,0 Mt. 43 % of these are from energy industries. (OSF 2017d.) The Finnish energy sector is facing a challenge with an objective of a nearly zero-emission energy system by the year 2050.

The production of combined heat and power (CHP) covers a large part of the electricity and heat production in Finland. 147,4 TWh of fuels were burned for electricity and heat production during the year 2016. The share of CHP production from this was 73,1 %. The share of separate heat production was 18,5 % and the share of separate electricity production 8,4 %. A large part of electricity and heat is produced with wood fuels. The most important fuels are hard coal, natural gas and peat and in separate heat production oil as well (OSF 2016a).

Emissions from energy production are regulated through the EU emissions trading system (EU ETS). EU ETS is based on a cap and trade -mechanism. Companies that have a lower cost of cutting down emissions sell their surplus emission allowances to companies for which it is more profitable to buy more allowances than to cut down emissions. 31 countries and 45 % of EU's greenhouse gas emissions are included in the EU ETS. (European Commission 2019.) In Finland fuels used in CHP production are also imposed to taxation. The taxation is based on 90 % of the amount of heat produced into the network. The tax for fuels burned in CHP production is cut to half compared to other fuel use. (Tax Administration 2016.)

When moving towards carbon neutrality three different perspectives must be considered carefully. The energy system must be cost-effective to facilitate economic growth and the competitiveness of Finnish companies in international markets. The system should be environmentally sustainable and able to secure the supply. (Ministry of Economic Affairs and Employment 2017.) The order of out-phasing is affected by fuel prices, taxation and emission prices (Pöyry Management Consulting Oy 2016).

Policies should be persistent but also flexible and prepared to work in varying circumstances because there are factors of uncertainty related to the technological development and the EU regulation in the future. According to the government platform the economic policy instruments should be neutral with respect to technology and based on the economical profitability. (Ministry of Economic Affairs and Employment 2017.)

The Finnish Parliament enacted a law banning the use of hard coal by 2029 the latest. There will also be an incentive of 90 million euros to give up hard coal before 2025 and it will be divided into half between CHP production and other production forms. (Ministry of Economic Affairs and Employment 2018.) The use of hard coal will be reduced with increasing the efficiency of the EU Emissions Trading System and adding different kinds of taxes and subsidies in order to improve the competitiveness of domestic fuels compared to hard coal. There will be no coal-related new investments in the power plants. (Ministry of Economic Affairs and Employment 2017.)

Based on current policies the use of renewable energy sources will grow through the increase in the use of forest-processed chips and by-products of wood industry and also with the help of new investments in wood industry. This will be promoted through energy taxation. (Ministry of Economic Affairs and Employment 2017.)

The energy and climate policy targets set strict guidelines to electricity and heat production in the future. Network is opening for different kinds of heat suppliers and production is becoming more decentralized and local. The growing share of low-energy and net zero-energy buildings is also causing certain expectations to the district heating system. (Paiho & Reda 2016.) Decentralized electricity and heat production based on renewable energy sources will be promoted through economical incentives (Ministry of Economic Affairs and Employment 2017).

Carbon-free power and heat production would be a huge step towards an entirely carbon neutral Finland. This master’s thesis exploits earlier studies on how Finland will transfer to the substitutes of fossil fuels in both CHP and separate heat production, especially with regard to hard coal. This phasing out process is observed by the national climate and energy strategy, previous scientific studies and future plans of energy companies. The focus, especially in numerical applications, is largely on the Helsinki area.

This thesis examines economic ways of phasing out hard coal from energy production. It seeks to find out an optimal tax levied on emissions from hard coal that will cause hard coal to phase out from the markets. The policy instrument is studied with an energy business model. The model is used to maximize the profit of different energy production methods: CHP plant consuming hard coal and wood pellet, heat only boiler (HOB) burning wood pellet and heat pump. In the model the energy is produced with fossil fuel, renewable fuel or both. The objective is to find the emission price in addition to emission allowance price that causes the profit from fossil fuel consuming energy production to be equal to the profits from different renewable production methods. When the use of hard coal is no longer profitable compared to renewable energy sources it will phase out from the market. Different applications are then analyzed and compared to one another.

2. Energy production and fossil fuel phase out

Finnish energy markets are strongly affected by two things. The electricity market is shared with some of the Nordic and Baltic Countries, which naturally bring our electricity market subject to changes on a larger scale and geographical areas. The electricity market in Finland can be divided to wholesale market and retail market. The wholesale market is for producers, large consumers and retail sellers. The retail market is for sellers and producers to sell the electricity bought from the wholesale market to the consumers. (Energy Authority 2017b.) Besides this the monopolistic position of district heating makes the Finnish heating markets quite unique.

CHP and separate heat production runs largely by fossil fuels. The share of wood based fuels and other renewable options are growing but there is still a lot of work to do before the objectives of the European Union and Finnish Parliament are reached.

2.1 The structure of energy production

Energy production in Finland can be divided into three lines of production: separate electricity production, separate heat production, consisting mostly of heat only boilers, and combined heat and power production. This study focuses on both separate heat production and CHP production since they are most relevant when concerning GHG emissions (OSF 2016a).

66,2 TWh of electricity were produced and 85,2 TWh were consumed in Finland in 2016. 78 % of the total consumption was produced in Finland and the rest was imported from the Nordic countries, Russia and Estonia. 32 % of the home production came from the production of combined heat and power. (OSF 2016a.)

Table 1. Electricity and heat production and fuels used by production mode in 2016. (OSF 2016a, OSF 2017a.)

	Electricity, GWh	District heat, GWh	Industrial heat, GWh	Fuels used, GWh
Separate production of electricity				
- Hydro power	15 634	-	-	-
- Wind power	3 068	-	-	-
- Solar power	18	-	-	-
- Nuclear power	22 280	-	-	-
- Condensing power	4 319	-	-	12 416
-Total	45 319	-	-	12 416
Combined heat and power production	**20 880**	**24 636**	**42 484**	**107 768**
Separate heat production	-	13 874	10 368	25 392
Total production	**66 200**	**38 510**	**52 853**	**145 576**
Net imports of electricity	18 951	-	-	-
Total	**85 150**	**38 510**	**52 853**	**145 576**

The majority of district heating, 64 %, was produced in CHP production and the rest came from separate heat production. Quite similarly 80 % of industrial heat was from CHP production and 20 % from separate production. (OSF 2016a.)

District heat (DH) plays an exceptionally large role in the Finnish heating system. Almost all densely built up areas have DH. The share of DH from the heat market is almost 50 %. In largest towns the market share can be over 90 %. DH in Finland can in fact be thought as a natural monopoly. Once joining the district heat network changing the heating system can precede technical and financial difficulties. (Finnish Competition and Consumer Authority 2011.)

The second largest heating form in Finnish residential and service buildings after DH is electricity. Other energy sources include heat pump, wood and gasoil each cover more or less 10 % of the total heating. The share of natural gas is 1 % and heavy fuel is 0,6 %. (Finnish Energy 2017a.)

Energy markets are strongly affected by the European Union emissions trading system. EU ETS covers all power plants that have a total heat capacity of 20 MW and smaller power plants that are connected to the same district heat network (Energy Authority 2017a).

2.1.1 Fuels and emissions

The fossil fuels used in energy production in Finland are oil, hard coal, natural gas, peat and other fossil fuels that contain for example coke and waste fuels. Besides these black liquor and other concentrated liquors, other wood fuels and other renewables are also used. Small amounts of other energy sources, such as hydrogen and electricity, appear as well. (OSF 2016b.)

In the year 2016 the production of district heat was 38,5 TWh and the production of heat in industrial purposes was 52,9 TWh. Nearly half of the district heat was produced with fossil fuels but 70 % of the industrial heat came from renewable energy sources. (OSF 2016a.)

Table 2. Coal, oil and peat consumption and emissions in CHP plants and HOBs in the year 2016. (OSF 2016b.)

	CHP plants		HOBs	
	Used amount, TWh	CO_2 emissions, Mt	Used amount, TWh	CO_2 emissions, Mt
Coal	15,4	5,2	1,2	0,4
Oil	0,7	0,2	4,2	1,1
Peat	11,3	4,4	2,3	0,9

Hard coal, peat and natural gas were the most utilized fuels in CHP plants among different wood fuels. The most common fossil fuels in separate production of heat were oil, peat and natural gas. (OSF 2016b.) The consumption of hard coal, oil and peat in CHP and heat production can be seen from Table 2. The share of hard coal in CHP production is significant in certain parts of Finland. Approximately 90 % of hard coal consumed in energy production in Finland in the year 2016 was used for CHP production in 8 different localities and one condensate power station. These are Helsinki, Espoo, Vantaa, Lahti, Turku region, Pietarsaari, Vaasa and the paper mill of Kirkniemi. (Pöyry Management Consulting Oy 2018.)

2.2 Phasing out hard coal

Pöyry Management Consulting Oy (2018) has examined the effects of a law against hard coal use in Finland. The report compares the effects of a hard coal ban effective from the year 2025 and 2030. It takes notice of the substitutive energy production methods, needs for investments and cost effects. The cost effects are assessed based on a price scenario from the government report on the National Energy and Climate Strategy for 2030 (Ministry of Economic Affairs and Employment 2017) and a low price scenario. In the National Energy and Climate Strategy scenario the emission allowance price in the year 2025 is 25 €/tCO^2 and 30 €/tCO^2 in 2030. In the low price scenario the emission allowance price is 7 €/tCO^2 and the price of electricity is expected to be low. Fuel taxation is assumed to remain unchanged until the year 2030.

Most of the plants using hard coal are switching to other energy sources during the years 2025-2030 because of local emission reduction targets and the effects of environmental policies on the hard coal price. Market-based reduction of hard coal would lead approximately to the amount of 6-7 TWh of hard coal burned in the year 2025 and 3,5-4,0 TWh in 2030. (Pöyry Management Consulting Oy 2018.)

2.2.1 Effects of the hard coal ban

The economic effects of the law against hard coal are caused by necessary changes in machinery and the costs of production. Some of the plants or machineries need to be replaced prematurely or additional investments have to be made to be able to change the fuels in use. The effects on the production cost of heat are assessed through capacity of production, fuel use, emissions and production of electricity. (Pöyry Management Consulting Oy 2018.)

According to Pöyry Management Consulting Oy (2018) depending on price scenario the hard coal ban in the year 2025 would lead to total costs of 190-200 million euros. The most significant part of the costs would be premature investments in five different locations. Ban in the year 2030 is reported to have costs of 14 million euros and premature investments in Helsinki and Vaasa region. The price of biomass in the future has significant effects on the realization of the costs.

The permitting procedures for new production plants can take up to ten years and for that reason investing in new technologies is not an option. According to Helen, the district heating producer of Helsinki, the time frame of the hard coal law forces faster options. The fastest way to replace hard coal is to increase the use of biomass significantly. (Talouselämä 2018.)

Because of the low and uncertain price of electricity several CHP plants will be replaced by HOBs and the capacity of electricity production will reduce. The marginal price of electricity is expected to rise as a result to giving up hard coal because the marginal cost of CHP-produced electricity is relatively low. Nevertheless the reduction in electricity production is small compared to the size of the electricity market. (Pöyry Management Consulting Oy 2018.)

Depending on the substitutive fuel the hard coal ban in Finland effects to the total GHG emissions of the country and at the EU level as well. A market stability reserve has been in operation since January 2019 as a way to control the surplus of emission allowances in the ETS. (European Commission 2019.)

2.2.2 Replacements for fossil fuels

There are several possibilities to integrate renewable energy sources to DH. For example heat pumps, waste heat, geothermal energy, solar energy, biogas, biomass and waste energy can all be utilized in a DH system. In the transition phase towards zero-emission energy system DH has an advantage, compared to for example separated heating methods, of having a possibility to combine renewable energy sources and conventional energy at relatively low cost. (Sayegh, Danielewicz et al. 2016.)

As stated in the Finnish National Energy and Climate Strategy (Ministry of Economic Affairs and Employment 2017) biomass is considered to be the number one alternative to conventional energy sources among CHP and heat production and this shows also in the report of the effects of the hard coal ban made by Pöyry Management Consulting Oy (2018). Heat pumps and waste heat are also planned on being utilized and in Helsinki natural gas as well. In both price scenarios and production methods (CHP and HOBs) studied by Pöyry Management Consulting Oy the production costs from using peat or biomass are smaller than from hard coal or gas.

Compared to hard coal biomass has poorer calorific value and storing possibilities. These lead to growing fuel transportation in both road- and marine traffic. According to Pöyry Management Consulting Oy (2018) the availability and price of biomass is uncertain, especially in the Helsinki region because of great demand and long distances to the areas of production. Biomass would have to be partly imported and in that case bigger markets also affect the availability and price.

The increase in the demand for energy wood has effects in commercial forestry in Finland and through importation other countries as well. Whether the imported biomass is a result of sustainable forestry or not affects to the actual benefits of burning biomass. According to the EU policy emissions from burning biomass are not taken into account in the calculated emissions since they are already counted in on the land-use, land use change and forestry sector (LULUCF). In a short term replacing hard coal with biomass would not reduce CO^2 emissions. (Pöyry Management Consulting Oy 2018.)

In the year 2016 the price of peat was lower than the price of biomass (OSF 2017b). This is also the case in the low price scenario in the report made by Pöyry Management Consulting Oy (2018). The Finnish government has planned to levy a tax on peat in such a way that keeps it competitive to fossil fuels but not to forest based energy sources (Ministry of Economic Affairs and Employment 2017). The emission factor of peat is higher than for example the emission factors of hard coal and natural gas (OSF 2018). Although peat is no longer categorized as a fossil fuel it has very similar GHG effects as hard coal in a 100 years term (Leinonen 2010). Being a local fuel and relatively easy to use it has benefits but from the perspective of climate change replacing hard coal with peat would be very harmful. Keeping the global temperature rise below 1,5−2°C compared to the pre-industrial level requires immediate and significant reductions in GHG emissions.

Heat pumps, geothermal energy, heat storages and nuclear power are examples of renewable energy sources that can take the place of hard coal in energy production. Integrating different energy sources and a heat storage to a DH system increases the use of renewable energy sources and makes the DH system more efficient. That way the system is not dependent on one single energy source and it is more flexible to meet the fluctuating heat demand. (Sayegh, Danielewicz, et al. 2016.)

The industrial heat pumps used for district heating get their thermal energy for example from ground, sea or wastewater. Heat pumps require electricity 15-50 % of the amount of heat produced. As long as electricity is produced with renewable energy sources heating from heat pumps is free from emissions as well. The need for electricity will increase significantly in the future. (Rinne, Auvinen et al. 2018.)

Hast, A., Rinne, S. et al. (2017) compared the economic aspects of heat storages and heat pumps with different capacities and solar collectors as a part of a DH system in southern Finland. The study discovered that the most profitable option is to combine heat storage (1 % of annual DH energy) and a heat pump (20 % of the peak heat demand). Also separately integrated large heat storages and large heat pumps are economical.

2.3 Phasing out in Helsinki

The consumption of DH in Helsinki covers more than 20 % of the total demand in Finland. There are two CHP plants, Hanasaari and Salmisaari B, and one HOB, Salmisaari A, using hard coal in Helsinki. 30 % of all hard coal used in electricity and heat production in Finland was burned in Helsinki and 60 % of DH in Helsinki was produced with hard coal. (Pöyry Management Consulting Oy 2018.) The magnitude of DH production and hard coal intensity in Helsinki makes it very unique when considering hard coal phase out.

The law against the use of hard coal has significant effects on energy production and new investments in Helsinki. If the hard coal ban were to come into effect in the year 2030 replacing hard coal with biomass could be possible if the biomass price remained 24 €/MWh by the year 2020 and 25 €/MWh by 2030, as assumed in the price scenario of the National Energy and Climate Strategy for 2030. Earlier schedule would lead to use of natural gas, considerably larger investments and costs. In both cases premature investments in Salmisaari CHP plant need to be made. New production capacity is estimated to utilize wood chips and wood pellets but also heat pumps are expected. (Pöyry Management Consulting Oy 2018.)

2.3.1 Helen Oy

The provider of DH in Helsinki, Helen Oy, has stated their plans towards zero-emission energy system. Hanasaari and Salmisaari B power plants are co-firing wood pellets among hard coal. A new pellet-burning heating plant has been put to test operation in the beginning of the year 2018 and new bio-heating plants are under consideration. The Hanasaari power plant is going to be closed by the year 2024. (Helen Oy 2018a.) The technical condition of Salmisaari B would allow it to be used until the 2030's but it is not capable of utilizing more than 5-10 % of wood pellets without making significant investments (Pöyry Management Consulting Oy 2018). Nevertheless Helen (2018a) has stated that the hard coal burned in Salmisaari power plant will somehow be replaced by renewable energy sources by 2040. Salmisaari A is expected to be shut down before the year 2030 (Pöyry Management Consulting Oy 2018). Helen also produces heating and cooling with heat pumps. Helen invested in a sixth heat pump with a heating efficiency of 18 MW to the Katri Vala heat pump plant in the year 2018. (Helen Oy 2018d.)

2.3.2 Future prospect in Helsinki

Hast, A., Syri, S. et al. (2018) studied the future of district heating in Helsinki, Espoo and Vantaa. The abovementioned plans for Helsinki DH system and the plans for Espoo (excess heat from a hospital and geothermal heat) and Vantaa (CHP plant using biofuels in 2019) DH systems create the reference scenario of the study. It was assumed that by the year 2030 coal and oil burned in CHP production would be replaced by 50 % natural gas and 50 % wood chips and by wood pellets in HOBs. By the year 2050 20 % of heat demand would be supplied by waste heat. Geothermal energy would cover 40 MW of heat output in Helsinki. Heat storage with the capacity of 1 % of the annual heat demand would be added to the DH system and carbon capture and storage would be invested in gas-fired plants.

Table 3. Future changes in the structure of energy production in Helsinki, Espoo and Vantaa. (Table modified from Hast, Syri et al. 2018.)

	Reference scenario	2030	2050
Heat production costs, €/ MWh_{heat}	50	39	58
Share of energy production in CHP plants, %	55	29	29
Share of energy production in HOBs, %	31	57	39
Share of energy production with heat pumps, %	14	14	32

The changes in the structure of energy production in the years 2030 and 2050 compared to the reference scenario in Helsinki, Espoo and Vantaa according to the study (Hast, Syri et al. 2018) are presented in Table 3. Heat production costs are expected to reduce by the year 2030. The increase in costs in the 2050 scenario is caused by the investments in CCS (Carbon Capture and Storage) technologies. The share of CHP production will decrease while the production in HOBs is expected to increase. The increasing share of energy production with heat pumps is due to the increase of waste heat and geothermal energy. (Hast, Syri et al. 2018.)

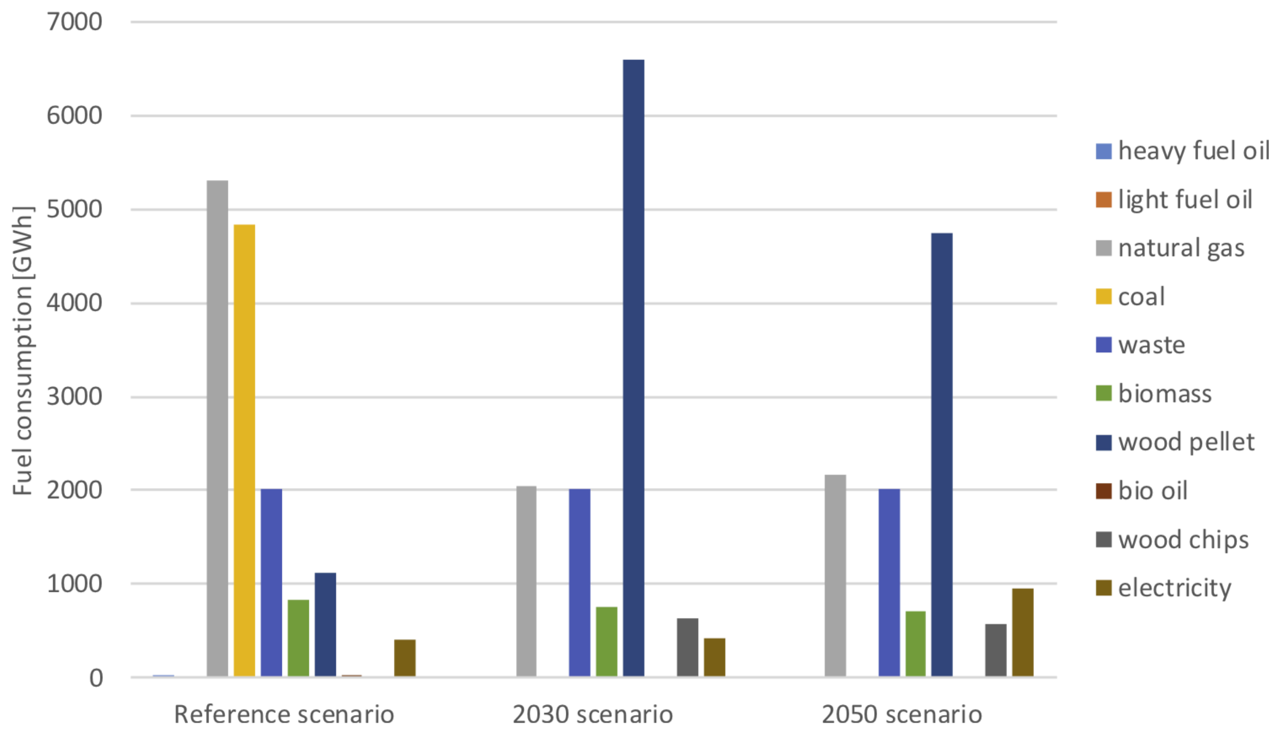

Fig.1. Fuel and electricity consumption in the DH systems of Helsinki, Espoo and Vantaa in different scenarios. (Figure from Hast, Syri et al. 2018.)

As can be seen from Figure 1, the consumption of coal in the energy production in Helsinki, Espoo and Vantaa is expected to end by the year 2030 and the use of natural gas will decrease by more than a half. The share of wood pellets will increase significantly. The sensitivity analysis for assumed fuel prices show that the prices of coal and natural gas have the largest effect on the heat production costs in the reference scenario. The 2030 and 2050 scenarios are most affected by the price of wood pellet. (Hast, Syri et al. 2018.)

Rinne, Auvinen et al. (2018) have presented a 100 % fossil-free scenario for Helsinki. It is based on 1100 MW of heat pumps that consume electricity produced with wind power. That is approximately ten heat pump plants the size of already existing Katri Vala heat pump plant. Small amounts of CHP production with biomass, HOBs, electric boilers and heat storages are also utilized in the scenario. The idea is to vary the different production methods according to the electricity price.

When it is windy and the price of electricity is low the heat pumps can produce energy to the heat storages. Later when the price of electricity is high the storages can be utilized and more heat can be produced with the biomass-burning CHP plant.

3. A theoretical model of electricity and heat production

The model is built to study the phase out of hard coal from energy production in Finland. It can also be used to examine phasing out other fuels. The model is based on a simple profit maximization problem. An energy company sets its production and input at a level that maximizes its profits. The input can be a fossil fuel or a renewable fuel. By comparing the profits of these two options the model aims to find the optimal tax that will cause hard coal to phase out from the market.

This study includes incineration plants that produce either electricity and heat or only heat. Both co-firing and single fuel power plants are taken into consideration in the model. The plants can be co-firing in such a way that they use both fossil and renewable fuels. The fuels used in co-firing plants can be peat, gas, coal, oil and bio fuels.

3.1 The model

The theoretical model to be developed here describes a single fuel power plant producing combined heat and power (CHP). The power plants use either fossil fuel x_f or renewable fuel x_r. The output of the production is $y = \eta x_i$, where $i \in \{f, r\}$ are fossil fuel and renewable fuel. η is the efficiency of the marginal technology. The energy efficiency may vary a little depending on the fuel choice but this is negligible. Based on literature (Lintunen & Kangas 2009, Baxter 2005) the efficiency coefficient can be thought constant regardless of the fuel distribution. For electricity production $\eta_e = 0{,}3$ and for heat production $\eta_h = 0{,}6$ (Lintunen & Kangas 2009).

The costs include direct input costs c_f and c_r and capacity costs $c^{cap}(x_i)$. The input costs are constant and the capacity costs are assumed to be convex: $c^{cap}_{x_i} > 0$. It is also assumed that the power plants run with full capacity.

The capacity cost function describes the impact of the use of input on the production costs helping to limit the use of inputs endogenously to the postulated capacity. The function of the capacity costs $c^{cap}(x_i)$ is similar to the one that Lintunen & Kangas (2009) have presented.

(1) $$c^{cap}(x_i; \mathcal{X}_{max}) = \kappa\left[(1-\mathcal{X})\frac{1-(1-\mathcal{X})^{-a}}{a} + \mathcal{X}\right]\mathcal{X}_{max},$$

where $\mathcal{X} = {x_i}/{\mathcal{X}_{max}}$ denotes the utilization rate of the plant and $\mathcal{X}_{max}$ is the maximal fuel input power. $a \in (0,1)$ and κ are shape defining parameters.

In the EU climate policy emissions from the use of renewables, such as wood, is not accounted in the energy sector to avoid double counting as their emissions are included in the land-use, land use change and forestry sector (LULUCF). Fossil fuels cause carbon dioxide emissions for the amount of $e = \varepsilon_f x_f$, where ε_f is the emission factor of input x_f. The climate policy is targeted at the fossil fuel use. According to the EU policy, the producer buys emission allowances equivalent to the amount of emissions produced. The price of an emission allowance is q. Additional emission price besides emission allowances is denoted as t and it can be for example an emissions tax.

3.2 Profit maximization of a CHP plant: fossil fuels versus renewable inputs under climate policy

The profit maximization of CHP production with a fossil fuel input is looked at first. After this a case of a renewable fuel input is examined and then compared to the fossil fuel case.

The electricity production part is competitive but on the part of the heat the production is a local monopoly that is setting the price on condition of the demand. The producer receives the price p_e for each unit of electricity output produced and the price p_h for heat. The case of a polluting fuel is examined first and thus the cost of the emissions is taken into account. The profit of the producer is

(2)
$$\pi_f(x_f, \phi_f) = p_e(1-\phi_f)\eta_e x_f + p_h(\phi_f \eta_h x_f)\phi_f \eta_h x_f - c_f x_f - c^{cap}(x_f) - (q+t)\varepsilon_f x_f$$

The problem of the producer is to maximize profit π_f with respect to input x_f and the share of production between electricity and heat, which is denoted by ϕ_f. Both $x_f \geq 0$ and $\phi_f \geq 0$.

The first order conditions (FOC) in case of a fossil fuel are:

(3a) $$\frac{\partial \pi_f}{\partial x_f} = p_e\eta_e(1-\phi_f) + (p_h + p_h'\phi_f\eta_h x_f)\phi_f\eta_h - c_f - c_{x_f}^{cap} - (q+t)\varepsilon_f = 0$$

(3b) $$\frac{\partial \pi_f}{\partial \phi_f} = -p_e\eta_e + p_h\eta_h + p_h'\eta_h^2\phi_f x_f = 0$$

The production will be increased until the marginal revenues are equal to the marginal costs. In case of the heat market the monopoly has market power; that is the producer can affect the price. The monopoly faces a downward sloping market demand curve. It sets its production lower than what would be the case in a competitive market. This leads to a higher price than the marginal costs.

The optimal share of production between electricity and heat is affected by the electricity and heat prices and the technological efficiencies as well as the market power of the monopoly. The optimal share of heat production grows if the price of heat or the efficiency of heat production grows. On the other hand it is optimal to reduce the share of heat production and increase electricity production if the price of electricity or the efficiency of electricity production grows. The optimal share of heat production will also grow if the market power of the monopoly grows.

These conditions together define the optimal fossil fuel input and production division $\{x_f^*, \phi_f^*\}$. With the optimal values the firm's profit is

(4)
$$\pi_f(x_f^*, \phi_f^*) = p_e(1-\phi_f^*)\eta_e x_f^* + p_h(\phi_f^*\eta_h x_f^*)\phi_f^*\eta_h x_f^* - c_f x_f^* - c^{cap}(x_f^*) - (q+t)\varepsilon_f x_f^*$$

Turning next to the case of renewable energy input, means that the CHP plant is not subject to climate policy. Hence, the target function (2) must be modified to reflect this case. The new profit function is given in equation (5). The profit function in case of a non-polluting fuel is otherwise similar to the polluting case but there is no cost of regulation:

(5) $$\pi_r(x_r, \phi_r) = p_e(1-\phi_r)\eta_e x_r + p_h(\phi_r\eta_h x_r)\phi_r\eta_h x_r - c_r x_r - c^{cap}(x_r)$$

The FOCs are:

(6a) $$\frac{\partial \pi_r}{\partial x_r} = p_e \eta_e (1 - \phi_r) + (p_h + p_h' \phi_r \eta_h x_r) \phi_r \eta_h - c_r - c_{x_r}^{cap} = 0$$

(6b) $$\frac{\partial \pi_r}{\partial \phi_r} = -p_e \eta_e + p_h \eta_h + p_h' \eta_h^2 \phi_r x_r = 0$$

x_r^* refers to the optimal amount of a renewable energy input that leads to maximum profit when only non-polluting fuels are used. As noted above, the firm will set its production on a level where the marginal revenues are equal to the marginal costs. With the market power of the monopoly the production is lower and the price is higher than on a competitive market.

With a growing electricity price and efficiency of electricity production it is economical to increase the production of electricity in relation to heat. Similarly, increasing the share of heat production is profitable when the price of heat and the efficiency of heat production are growing. The market power of the monopoly affects the heat price and therefore a larger market power leads to a larger share of heat production.

When comparing the FOCs to the fossil fuel case it can be seen than they differ only in the cost terms. The cost of the climate policies, emission allowance price q and the additional emission price t, are missing from the renewable fuel case.

It is assumed that the total costs in the fossil fuel case are lower than in the renewable fuel case even though fossil fuels are subject to climate policies. Currently input costs from fossil fuels, c_f, are lower than input costs from renewable fuels, c_r, and even with the current emission allowance price the profit from producing energy with renewable fuels is lower compared to conventional production. For this reason it is worthwhile to examine the additional emission price t.

The profit in the optimal case with a renewable fuel input is

(7) $$\pi_r(x_r^*, \phi_r^*) = p_e(1 - \phi_r^*) \eta_e x_r^* + p_h(\phi_r^* \eta_h x_r^*) \phi_r^* \eta_h x_r^* - c_r x_r^* - c^{cap}(x_r^*)$$

An optimal additional emission price for fossil fuels can be determined through the profits of the polluting and non-polluting production.

(8) $$t: \pi_f^*(t) - \pi_r^* = 0$$

3.3 Profit maximization of a heat production plant: fossil fuels versus renewable inputs under climate policy

The model for a heat production plant is similar to the one above but without the electricity production. The heat producing monopoly company maximizes it's revenues subtracted with input cost, capacity cost and emission related costs. With a polluting fossil fuel input the firm's profit is:

(9) $$\pi_f(x_f) = p_h(\eta_h x_f)\eta_h x_f - c_f x_f - c^{cap}(x_f) - (q+t)\varepsilon_f x_f$$

The profit π_f is maximized with respect to input x_f when $x_f \geq 0$. Thus the first order condition is:

(10) $$\frac{\partial \pi_f}{\partial x_f} = (p_h + p_h' \eta_h x_f)\eta_h - c_f - c_{x_f}^{cap} - (q+t)\varepsilon_f = 0$$

As in the previous model the production will be set on a level where the marginal revenues are equal to the marginal costs. The market power of the monopoly shows in the price of the product. The monopoly faces a downward sloping market demand curve. The higher price is a result of the monopoly's choice to produce less than on a competitive market.

With the optimal input choice the maximum profit of the firm is:

(11) $$\pi_f(x_f^*) = p_h(\eta_h x_f^*)\eta_h x_f^* - c_f x_f^* - c^{cap}(x_f^*) - (q+t)\varepsilon_f x_f^*$$

The same is conducted to the renewable fuel input. The target function reflects a case where heat is produced with a renewable fuel and therefore the costs of climate policies do not influence the production. The profit of the producer is:

(12) $$\pi_r(x_r) = p_h(\eta_h x_r)\eta_h x_r - c_r x_r - c^{cap}(x_r)$$

The FOC is:

(13) $$\frac{\partial \pi_r}{\partial x_r} = (p_h + p_h' \eta_h x_r)\eta_h - c_r - c_{x_r}^{cap} = 0$$

As stated before marginal revenues and marginal costs determine the level of the production. The monopoly produces less than a company on a competitive market would and for that reason the price is higher compared to competitive market. Even though the emission allowance price and the additional emission price do not apply to renewable fuels the costs in a renewable fuel case are larger than in a fossil fuel case. Currently fossil fuels are competitive to renewable fuels due to fuel prices and taxation.

The optimal amount of the renewable input leads to profit:

(14) $$\pi_r(x_r^*) = p_h(\eta_h x_r^*)\eta_h x_r^* - c_r x_r^* - c^{cap}(x_r^*)$$

Similarly to the CHP plant, the adequate emission price for the fossil fuel can now be determined from these two profit functions:

(15) $$t\colon \pi_f^*(t) - \pi_r^* = 0$$

4. Numerical model of CHP plant

This chapter presents the data on which the applications are based on. After that, the demand function of district heat is developed. It is constructed from past district heat prices. All numerical applications are thoroughly described and after that the specified data related to these numerical applications is presented. The model is applied in a way that is useful and up to date when designing environmental policies towards a carbon neutral energy sector. Recent data has been used in order to achieve as truthful results as possible to service future purposes.

4.1 Data

The electricity price p_e is based on the SPOT-prices of the Nordic electricity market Nordpool, which is the wholesale market for electricity producers, retail sellers and large consumers. These statistics are provided by Energy Authority (2018a.) p_e is an average of daily prices, which are averages of hourly prices from the year 2017. The price function of heat p_h is based on district heat prices from a larger time scale (OSF 2017b, OSF 2017c). The precise structure of the price function can be seen in subchapter 4.1.1.

The energy price data is mainly provided by Statistics Finland (OSF 2017b). Prices are an average of monthly or quarterly prices from the year 2016. Oil price is solely the price of light heating fuel oil as that covers the majority of oil use in heat production. Peat price is more accurately the price of milled peat. The price of forest industry by-products is gathered by Metsälehti (2018). Energy taxes are reported separately as they vary a lot between different fuels and different energy production methods (Tax Administration 2016, Tax Administration 2018a, Tax Administration 2018b). Transportation costs are included to prices if they are relevant to the case, such as peat.

Data regarding the capacity cost is provided by Lintunen & Kangas (2009). All other cost assumptions are by Hast, Syri et al. (2018).

The average ETS emission price from the first ten months of the year 2018 is 14,94 €/tCO^2eq (Markets Insider 2018). It is assumed that the price will keep on increasing due to environmental policies. The ETS emission price is modeled to be 30 €/tCO^2eq in the year 2030 (Hast, Syri et al.

2018), 40 €/tCO^2eq in the year 2035 and 90 €/tCO^2eq in the year 2050 (European Commission 2016).

The emission factors are from the Fuel classification of Statistics Finland from the year 2018 (OSF 2018). The types of peat and oil are chosen correspondingly to their prices. Carbon dioxide emissions of the biofuels are not counted in as greenhouse gases at this point of production and they are not included in the emissions trading scheme. Different kinds of conversion factors are needed regarding the prices and energy contents of some fuels. These factors are from Statistics Finland (OSF 2018) and Pellettienergia (2018).

All production related information about Salmisaari and Hanasaari power plants in Helsinki can be found from the Corporate Social Responsibility Report of the year 2017 of Helen Oy (Helen Oy 2018b). Correspondingly the business related data is from the Business year report of the year 2017 (Helen Oy 2018c). Helen Oy (2016) has also provided all information about the new pellet-burning HOB in Salmisaari. The data regarding the emissions of different power plants is provided by Energy Authority (2018b).

4.1.1 Demand function of district heat

The heat producer faces a demand function of district heat and this must be developed. This is based on Boardman, Greenberg et al (2011). A simple way for developing the function is to assume that the demand is linear. Here it is generated to correspond to past district heat prices and consumption.

The inverse demand function of district heat is determined using the linear demand function formula

(16) $$y = a - bp$$

(17) $$\frac{dy}{dp} = -b$$

where y is the demanded quantity, p is price and b is the change in demand when the price grows. The price elasticity of demand is determined from yearly average district heat prices and consumption of years 2007 and 2016 (Finnish Energy 2017b). Thus the price elasticity of demand is -0,26 which is quite inelastic. With the price and consumption b and a can now be solved.

(18a) $$0{,}26 = b\,\frac{77{,}74\ ^{€}/_{MWh}}{19594000\ MWh}$$

(18b) $$b = 65\,491{,}18$$

(19a) $$19594000\ MWh = a - 65491{,}18 * 77{,}74\ ^{€}/_{MWh}$$

(19b) $$a = 24685284{,}3$$

Thus the price function for heat is

(20) $$p_h = \frac{24685284{,}30 - y}{65491{,}18}$$

where y is the demand of district heat.

4.2 Numerical application

The numerical application follows the theoretical model closely although some modifications have been made to reflect more accurately reality. For example the numerical model takes notice of operation and maintenance costs for HOBs and CHP plants as well as investment costs. All data related to the numerical applications is presented in the subchapter 4.2.1.

The first calculation tries to represent the situation of Salmisaari B power plant in Helsinki. Salmisaari B is a CHP plant burning mostly hard coal and also small amounts of wood pellet. The limits set to this optimization are following the Salmisaari B power plant conditions. The amount of heat produced in one year is set to 1 900 GWh and the amount of electricity is set to be between zero and 900 GWh. The prices of electricity and heat are both set to 55 €/MWh in order to follow more realistic conditions.

An optimization is conducted as presented in the theoretical model. In this case the co-firing CHP production model is being used, as there are two different fuels in use. The profit is being maximized with respect to inputs, both fossil fuel and renewable fuel, and the share of production between electricity and heat. The emission allowance price is set to 20 €/tCO^2. At first the additional emissions tax is set to 0 €/tCO^2 and then modified gradually up to 25 €/tCO^2. For comparison this is done twice; first with the electricity efficiency coefficient of 0,3 and then 0,4.

Another numerical application follows the conditions of the new pellet-burning HOB in Salmisaari, Helsinki. This optimization utilizes the single fuel HOB model. An investment cost of 22 million euros is being divided to annual payments and then added to the costs.

Last a numerical application is conducted to a heat pump investment with a capacity of 20 MW. The investment cost is 10,6 million euros and it is also divided to annual payments.

The profits of these different scenarios are compared and with this information it is possible to find the energy policy that leads to equal profits from renewable and fossil fuel production. Finally the costs and amounts of emissions in these different scenarios are calculated and compared in order to find out the emission reductions of these actions.

4.2.1 Data related to the numerical applications

Table 4 presents fuel related parameters. In the theoretical model fuel taxes are included to the direct input costs c_f and c_r but in the numerical applications the components of taxes need to be scrutinized more closely. The fuel taxes of hard coal, oil and peat apply to separate heat production as they are. From CHP production the tax is collected from an amount of fuel calculated by the amount of heat delivered to consumption multiplied by 0,9. Each fuel is considered to be used in proportion to electricity and heat production. In addition to this the tax is cut to half regarding heating fuel oil, hard coal and natural gas among CHP production. (Tax Administration 2016.)

Table 4. Fuel related parameters. (Metsälehti 2018; OSF 2017b; OSF 2018; Tax Administration 2018a; Tax Administration 2018b.)

	Parameter	Unit	Hard coal	Oil	Peat	Forest chips	Wood pellets and briquettes
Fuel price	c_f, c_r	€/MWh	8,19	36,89	13,29	20,89	28,20
Fuel tax	c_f, c_r	€/MWh	29,46	23,79	1,90	0	0
Emission factor	ε	t/MWh	0,336	0,265	0,387	0	0

The production related parameters for a co-firing CHP plant and a single fuel HOB are a mixture of information from previous literature and realistic conditions from Salmisaari B power plant and a pellet burning HOB in Salmisaari, Helsinki.

Table 5. Production related parameters. (Helen Oy 2016; Lintunen & Kangas 2009.)

	Parameter	Unit	CHP, co-firing	HOB, single fuel
Efficiency coefficient, electricity	η_e	MWh/MWh	0,3 (0,4)	-
Efficiency coefficient, heat	η_h	MWh/MWh	0,6	0,8
Utilization rate of the plant	X	MW	1	1
Maximal fuel input power	X_{max}	MW	500	100
Function shaping parameter	κ	-	0,001	0,001
Function shaping parameter	a	-	0,9	0,9

The function shaping parameters are related to the capacity cost function. Operation and maintenance costs are taken into account in the numerical applications. Electricity distribution costs and electricity tax are required to determine the operating cost of heat pumps.

Table 6. Other costs. (Hast, Syri et al. 2018.)

	Unit	
Operation and maintenance costs, CHP	€/MWh $_{\text{electricity}}$	4,00
Operation and maintenance costs, HOB	€/MWh$_{\text{heat}}$	5,00
Electricity distribution cost	€/MWh	21,00
Electricity tax	€/MWh	22,50

Table 7 presents costs related to heat pumps. The unit cost of production consists of electricity spot price, electricity distribution cost and electricity tax. Besides this operation and maintenance cost and investment cost are included in numerical applications.

Table 7. Costs related to heat pump. (Hast, Syri et al. 2018.)

	Unit	Heat pump costs
Unit cost of production	€/MWh_{heat}	Electricity spot price + distribution cost + electricity tax
Variable operation and maintenance cost	€/MWh_{heat}	5,00
Investment cost	€/MW	530 000

5. Results

Recall, the aim of simulation, was to determine what the emission tax rate is required on top of the emission allowance price in order to phase out hard coal from production.

5.1 Optimization results

The first numerical application is reflecting the current situation of Salmisaari B power plant in Helsinki. The CHP production plant is burning hard coal and wood pellets. In the model the energy company naturally prefers the less expensive fuel and for that reason only one fuel is utilized at a time. The production switches from hard coal to wood pellets as costs from using hard coal grow. The emission allowance price is set to 20 €/tCO^2. At first the additional emissions tax is set to 0 €/tCO^2 and then gradually raised. Table 8 provides results of the optimizations when the efficiency coefficient for electricity is 0,3. The baseline situation is optimized first. With an emission allowance price of 20 €/tCO^2 the firm's yearly profit with an optimal input and an optimal share of heat production is 33,27 million euros.

The turnover of Salmisaari B power plant is estimated to be roughly 140 million euros. The baseline case of the optimizations results in 154 million euros revenues. As far as the profit is concerned the baseline situation corresponds to reality when the operating profit of the Salmisaari B CHP plant is approximately 18 % of net sales. The profit of the entire Helengroup is 10 % of net sales.

Table 8. Optimization results of Salmisaari B CHP plant when η_e is 0,3.

Case	**Salmisaari B, CHP optim. 1**	**Salmisaari B, CHP optim. 2**	**Salmisaari B, CHP optim. 3**
Electricity price, €/MWh	55	55	55
Heat price, €/MWh	55	55	55
Fuels, MWh			
Hard coal	6166666,67	3166666,67	3166666,67
Peat			
Wood pellets and briquettes	0	0	0
Heat pump, fuel & operating costs			
Share of heat production in CHP	0,51	1	1
Emissions tax, €/tCO2eq.	0	5	10
ETS carbon price, €/tCO2eq.	20	20	20
Tax+ETS carbon price, €/tCO2eq.	20	25	30
$Y_{electricity}$, MWh	899999,92	0	0,00
Y_{heat}, MWh	1900000,17	1900000,00	1900000,00
Emissions, tCO2eq.	2072000	1064000,00	1064000,00
REVENUES, €	154000004,56	104500000,00	104500000,00
COSTS, €	120733302,37	77723300,50	83043300,50
PROFIT, €	33266702,19	26776699,50	21456699,50
Case	**Salmisaari B, CHP optim. 4**	**Salmisaari B, CHP optim. 5**	**Salmisaari B, CHP optim. 6**
Electricity price, €/MWh	55	55	55
Heat price, €/MWh	55	55	55
Fuels, MWh			
Hard coal	3166666,67	0,00	0,00
Peat			
Wood pellets and briquettes	0	3166666,67	3166666,67
Heat pump, fuel & operating costs			
Share of heat production in CHP	1	1	1
Emissions tax, €/tCO2eq.	15	16	20
ETS carbon price, €/tCO2eq.	20	20	20
Tax+ETS carbon price, €/tCO2eq.	35	36	40
$Y_{electricity}$, MWh	0,00	0,00	0,00
Y_{heat}, MWh	1900000,00	1900000,00	1900000,00
Emissions, tCO2eq.	1064000,00	0,00	0,00
REVENUES, €	104500000,00	104500000,00	104500000,00
COSTS, €	88363300,50	89300000,50	89300000,50
PROFIT, €	16136699,50	15199999,50	15199999,50
Additional information: hard coal $x_f \geq 0$, pellet $x_r \geq 0$, $0 \leq \phi \leq 1$, $0 \leq Y_{electricity} \leq 900000$, $Y_{heat}=1900000$			

Table 8 shows the results of the optimizations when the emissions tax goes from 0 €/tCO^2 to 20 €/tCO^2. The increasing costs and decreasing profits are a result to tightening climate policies. As the emission tax rises from 0 €/tCO^2 to 10 €/tCO^2 the profit reduces from 33,27 million to 21,46 million euros. When the emission allowance price is 20 €/tCO^2 and a tax is added and set to 16 €/tCO^2 the use of hard coal is no longer profitable compared to wood pellets and the modeled CHP plant starts utilizing wood pellets instead of hard coal. Since the combined tax and emission allowance price has no direct effect to the costs of burning wood pellets, the costs and profits of energy production stay stable even though carbon price increases, as can be seen in Figures 2 and 3. At this point the profit of the energy production is 15,20 million euros.

According to the calculations the optimal share of heat production when producing combined heat and power is 51 % when there is no emissions tax. With an emissions tax set to 5 €/tCO^2 or more the optimal share of heat production is 100 %. This is due to the smaller technological efficiency of producing electricity compared to heat production. Based on the model the yearly emissions of the CHP plant are 1 064 000 tCO^2. This is very close to the actual yearly emissions of the Salmisaari B CHP plant. In the year 2017 the emissions from Salmisaari B were 962 426 tCO^2 (Energy Authority 2018b). There are no emissions of the production when only renewable fuel is used.

If the Salmisaari B power plant keeps burning hard coal even as the added tax is over 16 €/tCO^2 the profits keep falling. This is presented in Table 9.

Table 9. Optimization results of Salmisaari B burning only hard coal.

Case	Salmisaari B, single fuel, 1	Salmisaari B, single fuel, 2	Salmisaari B, single fuel, 3
Electricity price, €/MWh	55	55	55
Heat price, €/MWh	55	55	55
Fuels, MWh			
Hard coal	3166666,67	3166666,67	3166666,67
Wood pellets and briquettes			
Heat pump, fuel & operating costs			
Share of heat production in CHP	1	1	1
Emissions tax, €/tCO2eq.	20	21	25
ETS carbon price, €/tCO2eq.	20	20	20
Tax+ETS carbon price, €/tCO2eq.	40	41	45
$Y_{electricity}$, MWh	0,00	0,00	0,00
Y_{heat}, MWh	1900000,00	1900000,00	1900000,00
Emissions, tCO2eq.	1064000,00	1064000,00	1064000,00
REVENUES, €	104500000,00	104500000,00	104500000,00
COSTS, €	93683300,5	94747300,50	99003300,50
PROFIT, €	10816699,50	9752699,50	5496699,50
Additional information: hard coal $x_f \geq 0$, $0 \leq \phi \leq 1$, $0 \leq Y_{electricity} \leq 900000$, $Y_{heat}=1900000$			

With an emissions tax of 20 €/tCO^2 the profit is only 10,82 million euros. If the emissions tax was 25 €/tCO^2 the profit of the production would be as low as 5,50 million euros.

As a comparison another numerical application is conducted of the Salmisaari B CHP plant -case. The situation in this is similar to the previous one in all parts except the efficiency coefficient of electricity. In this case η_e is set to 0,4. These results are presented in Table 10.

Table 10. Optimization results of Salmisaari B CHP plant when η_e is 0,4.

Case	**Salmisaari B, CHP optim. 1**	**Salmisaari B, CHP optim. 2**	**Salmisaari B, CHP optim. 3**
Electricity price, €/MWh	55	55	55
Heat price, €/MWh	55	55	55
Fuels, MWh			
Hard coal	5416666,67	5416666,67	5416666,67
Peat			
Wood pellets and briquettes			
Heat pump, fuel & operating costs			
Share of heat production in CHP	0,58	0,58	0,58
Emissions tax, €/tCO2eq.	0	5	10
ETS carbon price, €/tCO2eq.	20	20	20
Tax+ETS carbon price, €/tCO2eq.	20	25	30
$Y_{electricity}$, MWh	900000,00	900000,00	900000,00
Y_{heat}, MWh	1900000,00	1900000,00	1900000,00
Emissions, tCO2eq.	1820000,00	1820000,00	1820000,00
REVENUES, €	154000000,00	154000000,00	154000000,00
COSTS, €	109550800,50	118650800,50	127750800,50
PROFIT, €	44449199,50	35349199,50	26249199,50
Case	**Salmisaari B, CHP optim. 4**	**Salmisaari B, CHP optim. 5**	**Salmisaari B, CHP optim. 6**
Electricity price, €/MWh	55	55	55
Heat price, €/MWh	55	55	55
Fuels, MWh			
Hard coal	5416666,67	5416666,67	
Peat			
Wood pellets and briquettes			3166666,67
Heat pump, fuel & operating costs			
Share of heat production in CHP	0,58	0,58	1
Emissions tax, €/tCO2eq.	15	16	17
ETS carbon price, €/tCO2eq.	20	20	20
Tax+ETS carbon price, €/tCO2eq.	35	36	37
$Y_{electricity}$, MWh	900000,00	900000,00	0,00
Y_{heat}, MWh	1900000,00	1900000,00	1900000,00
Emissions, tCO2eq.	1820000,00	1820000,00	0,00
REVENUES, €	154000000,00	154000000,00	104500000,00
COSTS, €	136850800,50	138670800,50	89300000,50
PROFIT, €	17149199,50	15329199,50	15199999,50
Additional information: hard coal $x_f \geq 0$, pellet $x_r \geq 0$, $0 \leq \phi \leq 1$, $0 \leq Y_{electricity} \leq 900000$, $Y_{heat}=1900000$			

The baseline situation is slightly different when the efficiency coefficient of the electricity is raised to 0,4. The optimal share of heat production is 58 % and the profit of the CHP production is 44,45 million euros. The profits are larger down the line compared to the previous case. The increase in profits is logical as the production is now more efficient.

As can be seen from Table 10 the increase of the efficiency coefficient of electricity lowers the optimal share of heat production and through this it has an effect to the input, revenues and costs. Nevertheless the studied effect of the combined tax and emission allowance price to the profit seems to be very similar as in the case of a lower efficiency coefficient. With the difference of only 1 €/tCO^2 the CHP plant switches over from hard coal to wood pellets when the tax reaches 17 €/tCO^2.

The new pellet burning HOB in Salmisaari, Helsinki burned 190 GWh of wood pellets in one year. With the efficiency coefficient of 0,78 it leads to 152 GWh of heat. The profit of the production is 0,78 million euros.

A heat pump with a heating capacity of 20 MW produces 114 GWh of heat. The profit of production with the heat pump is 1,26 million euros. The cases of these renewable energy sources are found from Table 11.

Table 11. Pellet burning HOB and heat pump investments.

Case	Pellet burning HOB in Salmisaari	Heat pump
Additional information	- investment cost 22M€, - yearly cost at 6 % interest and 40 years service life of technology is 1,46 M€	-heating capacity 20MW -investment cost 0,53M€/MW -yearly cost at 6 % interest and 40 years service life of technology is 0,70M€
Electricity price, €/MWh	55	55
Heat price, €/MWh	55	55
Fuels, MWh		
Hard coal		
Peat		
Wood pellets and briquettes	190000	
Heat pump, fuel & operating costs		4313000
Share of heat production in CHP		
Emissions tax, €/tCO2eq.		
ETS carbon price, €/tCO2eq.		
Tax+ETS carbon price, €/tCO2eq.		
$Y_{electricity}$, MWh		
Y_{heat}, MWh	152000,00	114000,00
Emissions, tCO2eq.	0,00	0,00
REVENUES, €	8360000,00	6270000,00
COSTS, €	7578000,10	5013000,00
PROFIT, €	781999,90	1257000,00

The investment costs of these energy production technologies are counted in. These are both considered to be renewable energy sources and for that reason there are no emissions from these energy production methods.

5.2 Graphical analysis of the results

The first profit maximization representing the situation of Salmisaari B power plant in Helsinki leads to yearly profit of 33,27 million euros. When the additional emission tax is gradually increased the costs from using hard coal are growing and the profit of production decreases. This is represented in Figure 2 and Figure 3.

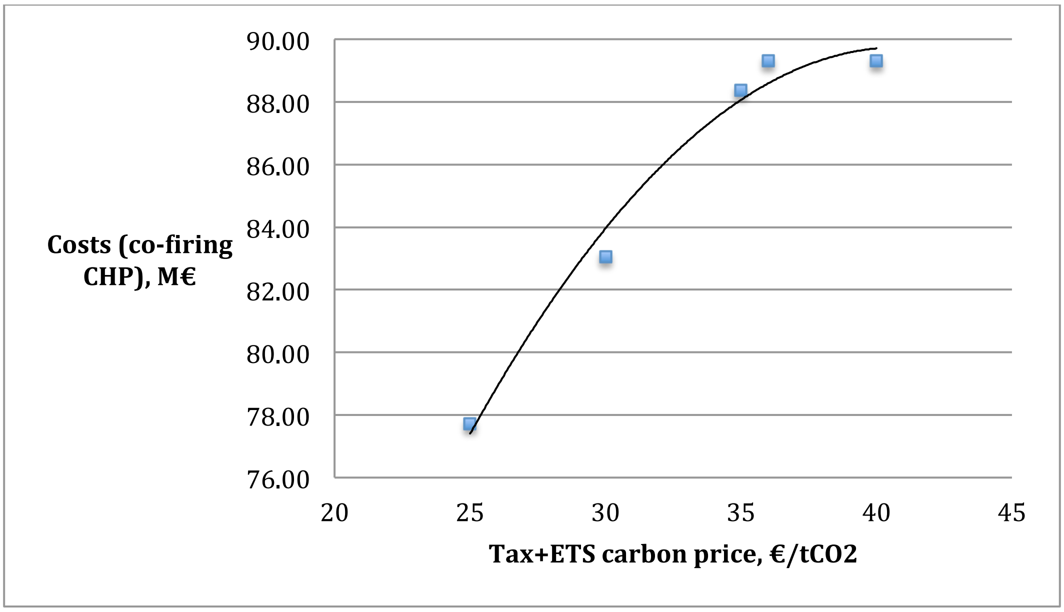

Fig. 2. The effect of the combined tax and emission allowance price to costs of production.

When the emission allowance price is 20 €/tCO^2 and the added tax reaches 16 €/tCO^2 the use of hard coal is no longer profitable compared to wood pellets. At this point the profit from the energy production is 15,20 million euros. The decrease in profits compared to the case of 20 €/tCO^2 emission price is 18,07 million euros. It should be noted that significant investments to technology are needed for the CHP plant to increase its share of wood pellet use. That investment cost is not taken into account here and for that reason switching to 100 % of wood pellets would not happen until with a higher emission price.

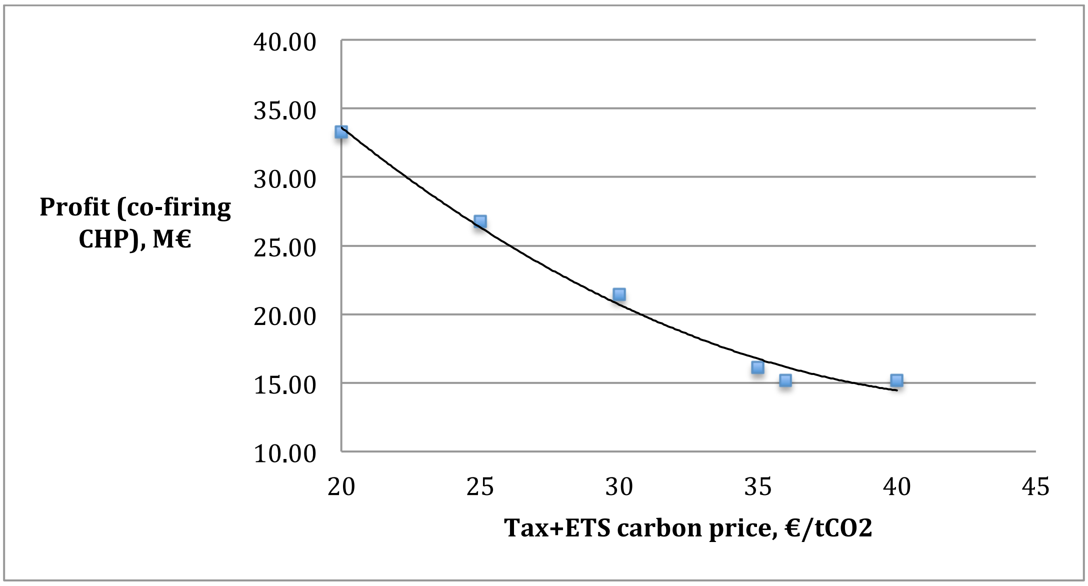

Fig. 3. The effect of the combined tax and emission allowance price to the profit of a CHP plant.

The pellet-burning HOB is set to produce 152 GWh of heat during one year. The amount of heat produced in the case of the Salmisaari CHP plant is 12,5 times the amount that the HOB produces. If a similar amount of heat were produced with several pellet-burning HOBs as the one in question here the yearly profit of the pellet-burning HOBs would be 9,77 million euros. Under these conditions when the emission allowance price is 20 €/tCO^2 and the tax reaches as high as 21 €/tCO^2 the pellet-burning HOBs would be a profitable investment compared to the Salmisaari B CHP plant burning hard coal.

The heat pump with a heating capacity of 20 MW produces 114 GWh of heat. To produce the same amount of heat with heat pumps as the CHP plant produces the heat pump production is multiplied with 16,67. The yearly profit of production with several heat pumps would be 20,95 million euros. With a tax of 11 €/tCO^2 it is more profitable to invest in heat pumps than to produce heat with hard coal. Figure 4 presents profits from the studied energy production methods compared to each other. With an increasing emission tax heat pump is the most profitable option for energy production.

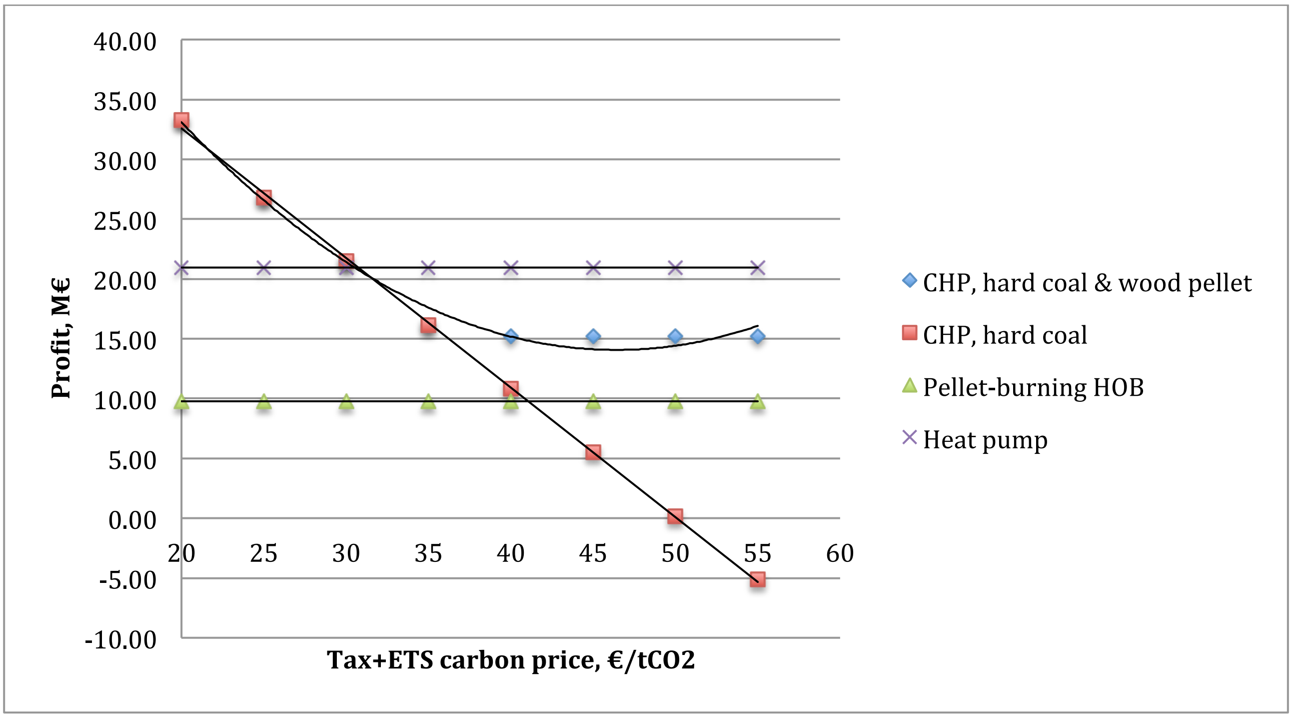

Fig. 4. The rising carbon price and profits from energy production.

According to the numerical application the CHP plant has yearly emissions of 1 064 000 tCO^2 when producing with hard coal. Accordingly replacing hard coal with renewable energy sources creates an emission reduction of the same amount.

If the energy company would invest in the pellet-burning HOBs as the combined tax and emission allowance price reaches 41 €/tCO^2 the loss in profit compared to the baseline situation would be 23,53 million euros. Similarly when investing to heat pumps as the combined tax and emission allowance price reaches 31 €/tCO^2 the loss would be 12,35 million euros. These can be thought as costs of the emission reduction of 1 064 000 tCO^2.

6. Conclusions

The objective of this thesis is to study the phase out of hard coal from the electricity and heat production in Finland. The transformation to renewable energy sources is studied through previous literature. This thesis seeks to find the price for emissions that causes the profit from fossil fuel consuming energy production to be equal to the profit from renewable production. This is studied by using an energy business model that was built specifically to combined heat and power production and separate heat production. The numerical applications concentrate on a CHP plant consuming hard coal and wood pellets, a HOB burning wood pellets and a heat pump. Costs and profits of these different options are compared. The structures of the numerical applications are closely related to the energy production in Helsinki.

An investment to pellet-burning HOBs is profitable compared to energy produced with hard coal at a combined tax and emission allowance price of 41 €/tCO^2. Investing to heat pumps would become profitable when the combined tax and emission allowance price reaches 31 €/tCO^2. An emission reduction of one million tons of carbon dioxide equivalent is achieved with the cost of 12,35 million euros when switching to heat pumps and 23,53 million euros when investing in the HOBs.

These results give an example of certain emission taxes required to phase out hard coal from energy production. The emission allowance prices were on the increase the whole year of 2018 and during September and October 2018 the prices were historically high. Even so at its current state the EU emission trading system alone is not enough to cause hard coal to phase out from energy production. Besides emissions trading other measures should be taken in order to achieve the climate and energy policy targets set by European Union and the Finnish Government.

The law against hard coal utilization will come into effect in the year 2029. According to the plans of Finnish Government and several energy companies giving up hard coal will for the most part be replaced with different wood based fuels. The amount of local logging waste is very limited and cutting timber for energy production doesn’t result to emission reductions in the needed time frame. There is a need for imported biomass and uncertainty about future prices of these fuels.

It is possible that a tax levied on emissions from hard coal would have been a better option than the hard coal ban. The costs of prematurely replacing machineries and investing to technologies that enable the extended fuel use are high. If a tax were used to phase out hard coal from energy production each company would make the decisions about their future investments based on their profit. The full useful life of current machineries would be better utilized which is naturally profitable. A more flexible schedule for replacing hard coal in energy production could also lead to well thought-out investments to new technologies and production methods. However, the hard coal ban in the year 2029 will lead to certain emission reductions in the imposed period of time, as long as the replacing energy production methods are truly causing less emission than the conventional production.

The CHP production consuming fossil fuels in Helsinki area and in whole Finland will be partly replaced by HOBs utilizing different renewable fuels and natural gas, which causes a reduction in the electricity production. However a large amount of electricity is needed for example for energy production with heat pumps and increasing amount of electric cars. Finding the most profitable, renewable way to cover this loss in electricity production is a subject to a possible future research. Besides this there are several research possibilities in the field of future energy production and energy market. In the next 30 years the energy field will inevitably go through significant changes regarding for example the shift to renewable energy sources, decentralized energy production and opening the network for different kinds of energy producers. These are definitely interesting topics to look into.

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